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Global socio-economic impacts of changes in natural capital and ecosystem services: State of play and new modeling approaches

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ABSTRACT

The year 2020 is a critical year for sustainable development policy and practice with the review and renewal of various international commitments including the Sustainable Development Goals, the Convention on Biological Diversity and the Paris Agreement. The post-2020 agenda needs to be informed by more robust analytical approaches that capture the interactions between the economy, society and the environment. In this paper, we review the state of the art in available models and datasets that lay the groundwork for future analytical work to inform this agenda. Based on this review, we propose an integrated modeling approach for global analysis to underpin international policy discourse and advocacy, and; a sub-global approach focusing on evaluating specific strategies and policy portfolios to make progress toward sustainability commitments considering detailed local country context. Both approaches rely on integrating whole of economy computable general equilibrium models with spatial land use land cover and ecosystem services models. Endogenizing feedbacks between modeling system components ensures that evidence is based on interactions between all system components. Recent advances in methods, data and available tools discussed herein reduce barriers to entry for this type of complex systems analysis and increases the timeliness of policy advice.

1. Introduction

Natural capital and the ecosystem services (ES) that it provides deliver many benefits to people (Daily, 1997; Millennium Ecosystem Assessment, 2005), while ES are a direct link between natural capital, the economy and society. The continued degradation of natural capital and loss of biodiversity compromises the flow of ES which has a detrimental impact on the well-being of current and future generations (IPBES, 2019). International initiatives such as the Convention on Biological Diversity (CBD), the United Nations (UN) Framework Convention on Climate Change (UNFCCC), the UN Sustainable Development Goals (SDGs), and the UN Convention to Combat Desertification all aim to tackle the decline in natural capital and ES. The 17 SDGs agreed to in 2015 are integrated goals that traverse natural capital, society and the economy, and recognize that they cannot be managed separately (United Nations, 2015).

In 2020, the High-Level Political Forum on the SDGs meets to review the first 5 years of progress toward the SDGs and providing an opportunity to renew commitments. Also, in 2020, the CBD will set a new framework and post-Aichi 2020 biodiversity targets and the Paris Agreement of the UNFCCC will begin implementation. All these events provide an opportunity to strengthen commitments to halting natural capital degradation and place special urgency on establishing robust analytical frameworks for designing and testing strategies moving

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forward.

Considerable effort by the global research community over the last few years has focused on understanding the current condition and future trends of natural capital and ES, for example, through the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), The Economics of Ecosystems and Biodiversity (TEEB), Rio Conventions, and the 2020 Review on the Economics of Biodiversity. But the impact to economies and societies of current and future trends of changes in natural capital and ES have been less studied outside the context of specific local case studies. There is an urgent need to improve understanding and communication of the importance of natural capital and ES to economic prosperity and human well-being at national to global scales, the potential impacts of maintaining and restoring ecosystems, as well as the consequences of inaction.

While IPBES includes socio-economic aspects in its assessments of the condition of natural capital, what is missing is knowledge of how the estimated changes to ES under various trends or scenarios could impact the economy, wealth and society. Furthermore, much analysis to date has focused on potential socioeconomic development scenarios such as the Shared Socioeconomic Pathways (O'Neill, 1997; Riahi et al., 2017), which are difficult to scale down to a level at which decision-makers can design public policy and investment.

Different modeling approaches than those found in the ES valuation literature are required for this type of assessment. This paper contrasts the anticipated needs of international initiatives to enhance natural capital and ES, with existing datasets, models and modeling initiatives to identify how they could be utilized to meet the needs of global commitments and identify key gaps in the knowledge base. We argue that a complex systems approach is required to capture the feedbacks between both economic and ecological systems and that this system can be represented by the interaction of economy-wide computable general equilibrium (CGE) models and spatial ES modeling. We propose a two-tier research agenda to address the gaps identified and develop more robust analytical frameworks to drive the post-2020 agenda.

The first tier focuses on national and subnational-scale analysis to inform national public policy and investment interventions while the second tier focuses on global-scale analysis to inform international policy discourse, negotiations and advocacy. At the national level, we present an overview of the Integrated Economic-Environmental Modeling (IEEM) Platform (Banerjee and Cicowiez, 2020; Banerjee et al., 2020c, 2019g, 2019f, 2016b) and how it can be used to explore narratives of natural capital and ES change. At the global scale, we discuss how the GTAP database (Aguiar et al., 2019) and multi-regional CGE modeling (Corong et al., 2017) could be linked to inform international discourse. To capture the interactions between economy, environment and society, both of these national and global frameworks can be linked with spatial ES modeling to quantify how public policy and investment affects both market and non-market ES supply and in turn, how economies adjust to these changes.

2. Background

2.1. Major needs of international initiatives to protect biodiversity

Although there has long been a need for initiatives that better model the dynamic relationship between natural capital, economy and society, the year 2020 places special urgency on demand for robust modeling because of several key milestones in the international policy agenda. First, action would need to be taken now to have enough time to mature and be reflected in biodiversity outcomes reached by 2030. Some of the SDG targets expire in 2020 and countries at the High-Level Political Forum will have an opportunity to extend those targets until 2030. The Biodiversity Leaders' Summit will take place during the UN General Assembly and in October 2020, the UN will decide on a new 10-year framework for biodiversity under the UN CBD at the 15th Conference of Parties. Finally, the international community will have an opportunity to enhance national action plans to ensure that the goals of the Paris Agreement are achieved during the 26th Conference of Parties of the UNFCCC in December 2020.

While there is intense political pressure raised by these crucial international events, natural capital and ES modeling needs to go beyond delivering to these landmark events. Our review and analysis show that the environmental and economic research community places importance on the following[1]:

- Integrated models are needed that are effective in assessing the interaction between the three pillars of sustainable development and wealth: the economy, society and the environment. Evaluating each component in isolation is insufficient and can result in misleading policy advice (Banerjee, 2019; Lange et al., 2018; Stiglitz et al., 2010, 2009).
- Scenarios that show how policy interventions can make progress toward biodiversity and SDG targets at the national level are most informative for policy formulation and action.
- Business as usual and baseline scenarios should incorporate how current trajectories of natural capital and ES decline will affect economies and society.
- Models and methods are needed that are consistent with the UN System of Environmental-Economic Accounting (SEEA) (United Nations, European Commission, et al. 2014) so linkages can be readily made to national systems for measuring economic performance, specifically, the System of National Accounts (SNA) (European Commission et al., 2009).
- Countries require information that explains why biodiversity loss matters and pathways to reverse current trends. Conversely, analysis that provides alternatives to enhance natural capital and ES is needed.
- The temporal periods to be modeled that have most relevan7ce for international initiatives, policy discourse and advocacy to protect biodiversity are through to the years 2030 and 2050.
- Relevant indicators are needed by all international initiatives and include those related to health, food, energy, water security, migration, demographic change, costs and benefits of conservation, macro-economic metrics, and supply and demand of natural capital and ES and their value.
- For modeling results to have wider acceptance by policy makers, it is critical that outputs have qualitative narratives and storylines, visual products including maps, and quantitative information on impacts at all scales and biomes (terrestrial and marine).
- Efforts should be prioritized where environmental change is likely to present particularly significant future economic risks and generate conflict, such as water scarcity and food security.

2.2. Existing datasets, information standards, models, and modeling initiatives to address needs of international initiatives to protect biodiversity

This section describes the state of the art in terms of datasets, information standards, models, and initiatives that have been used to assess how the quality of natural capital and ES can be affected by different global and local policies.

2.2.1. Biodiversity and ecosystem service models

The following Ecosystem Service Modeling (ESM) frameworks focus on ecosystems and how their quality changes over time under business as usual and policy intervention scenarios. Some recent frameworks consider some social and economic factors as drivers of environmental change,

[1] A thorough literature review and consultation process with key stakeholders of these political initiatives was conducted by the authors to arrive at the needs identified here. For more, see Crossman et al. (2018).

though they fall short in considering the dynamic interactions of the system and how changes in natural capital and ES affect the economy and in turn, how economies respond and affect natural capital and ES.

The Madingley model is a General Ecosystem Model developed principally by the UN Environment Programme World Conservation Monitoring Centre and Microsoft Research at Cambridge University (Bartlett et al., 2016; Harfoot et al., 2014). The model aims to inform decision-makers about the impacts of their choices on natural capital and ES, and on trajectories of change under different scenarios of human development. The model simulates the flows of biomass of collections of species based on a series of fundamental ecological processes, such as consumption, metabolism, growth, reproduction, dispersal, and mortality. The model lacks feedback loops between the economy and the environment.

Generalised Dissimilarity Modeling (GDM) (Ferrier et al., 2007; Fitzpatrick et al., 2011; Laidlaw et al., 2016) is a statistical technique for analyzing and predicting spatial patterns of plant or animal presence across large regions. GDM can be adapted to accommodate special types of biological and environmental data including information on how species are genetically related to one another and information on barriers to how they can spread spatially. The approach can be applied to a wide range of assessment activities including visualization of spatial patterns in community composition, species distribution, conservation assessment, and climate-change impact assessment.

The International Institute for Applied Systems Analysis (IIASA) Global Biosphere Management Model (GLOBIOM) (Havlík et al., 2011; Obersteiner et al., 2016) is used to analyze global to regional competition for land and assess the sustainable production of food, forest, fiber, and bioenergy. A partial equilibrium economic model allocates land uses given the objective of maximizing consumer/producer surpluses, with rules defined by scenarios, targets and production constraints. The representation of biodiversity is limited to inputs of 6 land cover classes and global biodiversity hotspots. Its more recent iteration assesses tradeoffs under achievement of some land related targets of the SDGs (Obersteiner et al., 2016).

Developed by the *Planbureau voor de Leefomgeving* (PBL) at the Dutch Environment Agency, the Global Biodiversity model (GLOBIO) is a modeling framework for estimating the impact of environmental drivers on biodiversity (Alkemade et al., 2009). GLOBIO is based on cause-effect relationships and uses spatial information on environmental drivers as inputs that are sourced from PBL's Integrated Model to Assess the Global Environment (IMAGE). GLOBIO compares the presence and mean abundance of certain species in degraded ecosystems with similar undisturbed ones for an estimation of biodiversity. GLOBIO addresses: (i) the impacts of environmental drivers on species abundance and their relative importance; (ii) expected trends under scenarios, and; (iii) the likely effects of various policy responses (Alkemade et al., 2009).

CLUMondo (Eitelberg et al., 2015; Ornetsmüller et al., 2016; van Asselen and Verburg, 2013) is a global model that simulates land system changes as a function of exogenously derived demand for land. The land use and land cover (LULC) map combines data on land cover, livestock density, and intensity of agricultural production. For each time period and for each grid cell, the model allocates demand for land to those grid cells with the highest transition potential. The transition potential is the sum of the local suitability, the conversion resistance and the competitive advantage of a land system. Related to the CLUMondo, CLUE is a flexible, generic land use methodology to model near future land use changes based upon actual and past land use conditions (Verburg and Overmars, 2009; Wassenaar et al., 2007) Changes in land use are allocated in the model by statistically analyzing the quantitative relationships between the actual land use distribution and potential drivers of change. CLUE accounts for scale dependencies of driving factors of land use change with a multi-scale approach that balances bottom-up effects of local conditions and top-down effects as a result of changes at national and regional scales.

The Integrated Model to Assess the Global Environment (IMAGE) was developed to analyze the dynamics of global, long-term environmental change and sustainability problems (Stehfest et al., 2014). IMAGE contains an ES module that quantifies the supply of eight ES. The ES are derived directly from other IMAGE components and include food provision from agricultural systems, water availability, carbon sequestration, and flood protection. Estimation of the ES of wild food provision, erosion risk reduction, pollination, pest control, and attractiveness for nature-based tourism requires additional environmental variables and relationships (Maes et al., 2013), in particular, fine-scale land-use intensity data from the GLOBIO model. IMAGE compares the supply of different services with estimates of the minimum quantity required to identify ES supply and demand imbalances. Results, for example, can indicate the minimum amounts of food and water required to maintain human health, or the minimum area of natural elements in a landscape to meet crop pollination demand.

ARtificial Intelligence for Ecosystem Services (ARIES) is a system for quantifying ES to improve policy and decision making. ARIES creates probabilistic models of both provision and usage of ES in a region of interest and maps the actual physical flows of those benefits to their beneficiaries. ARIES is building a user community whereby users contribute and improve ES data and models which are shared (Martínez-López et al., 2019; Villa et al., 2014) according to FAIR (Findable, Accessible, Interoperable and Reusable) data principles (Wilkinson et al., 2016).

The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) is a toolbox used to investigate the changes in supply of approximately 19 ecosystem services under different user-defined scenarios, such as land use and climate change (Sharp et al., 2020). Users prepare spatial data and biophysical parameter files prior to running individual ES tools. InVEST is the most widely used ES modeling framework with a relatively easy to use interface and extensive documentation of each ES modeling tool.

System Dynamics (SD) modeling links economic and ES models. SD is an umbrella term for a group of models developed to explore system behavior and has been extended to linking economic and ES modeling, for example, in green economy modeling (Bassi, 2015; Bassi et al., 2016; UNEP, 2014). SD models are developed in participatory settings and can be used as to compare changes in a system under alternative scenarios. Threshold 21 supports long-term national development planning by comparing different policy options for meeting a specific goal across a wide range of sectors (Millennium Institute, 2015). It includes linkages between the economic, social, and environmental spheres however, it does not integrate feedbacks between them.

The Global Unified Metamodel of the Biosphere (GUMBO) is an SD tool to maximize outcomes based on economic development, population and climate change scenarios. GUMBO is a predecessor to the Multiscale Integrated Earth Systems Model (MIMES) which itself is a SD model of human-environment systems at different scales. GUMBO/MIMES simulate future land use changes across different land use types, based on economic and ES production functions.

The International Futures Simulator (IFs) is a large-scale, long-term, integrated global SD model (Hughes et al., 2012; Hughes and Johnston, 2005) to explore global futures through alternative scenarios. The model represents demographic, economic, energy, agricultural, socio-political, and environmental subsystems for 183 countries interacting with biodiversity. This system, however, lacks the spatial detail required to accurately represent the localized nature of ES and its interaction with the economy.

Bioeconomic-models are either biological process models with an added economic component or economic optimization models which include bio-physical components among optimization choices (Brown, 2000). They operate at various scales, including farm models, landscape, models, and regional and national models, both in static and dynamic form (Flichman and Allen, 2014). Of interest to this paper are the regional and national models.

In this category we find the Sustainable Options for Land Use Model (SOLUS), which uses linear programming to explore long-term policy impacts on economic and environmental sustainability, understood as economic surplus, employment; nitrogen, phosphate and potassium balance; and denitrification (Bouman et al., 1999).

The Mali Bio-Economic Farm Household Model (Ruben et al., 1998) is an extension of traditional farm household models that uses a linear farm household optimization model with endogenous resource endowments and bio-physical processes to assess farmer responses to agrarian policies and their effectiveness to improve farm income and soil fertility. Farm households are aggregated to the regional level to assess the supply response and the potential price effects when interacting with demand (Flichman and Allen, 2014).

The EPIC regional agricultural model using a plant growth simulation program as activities generator (Deybe and Flichman, 1991) uses information from biophysical modeling to analyze impacts of price changes on production levels, farmers' income and erosion levels simultaneously. As a more developed version of the previous, the Multilevel Analysis Tool for Agricultural Policy model (MATA) is a dynamic-recursive model that allows ex-ante simulation of impacts of agricultural policies on economic welfare at aggregate levels (Deybe, 1998).

The Cost Benefit Analysis for Sustainability Model (COBAS) is a dynamic bio-economic model of fisheries that includes the interlinkages between that sector and other industries, designed to assess industry and community led stock recovery plans (Ulrich et al., 2002). It includes biological and economic components of the fishing sector, as well as the recreational sector and regional economy (Flichman and Allen, 2014).

On another line of work, the Ecological Footprint (Rees and Wackernagel, 1996) is an indicator that accounts for human demand on global that compares the level of consumption with the available amount of bioproductive land and sea area meant to highlight when sustainability has exceeded a sustainable threshold (Wiedmann and Barrett, 2010). The concept of Ecological Footprint is not a model, but a collection of indicators that have been included in various types of models and quantify various factors, such as crop productivity, overgrazing, desertification, land erosion, eutrophication, deforestation, threat to species, biodiversity, overfishing, water shortages. National Footprint Accounts (NFA) use data from the United Nations Food and Agriculture Organization related to production, imports, exports and yields for agriculture, forestry and fisheries to calculate the net consumption of a nation and the associated appropriation of land which takes place due to that consumption both nationally and abroad (Wiedmann and Lenzen, 2007). This appropriation of land is measured in Global Hectares defined as "the annual productivity of one hectare of biologically productive land or sea with world-average productivity" (Wiedmann and Barrett, 2010). Footprint analysis has been combined with regional Input-Output studies to determine the resource and pollution content of inter-regional and inter-national trade flows with principal applications using input–output enabled databases such as Eora Multi Regional Input-Output—MRIO—(Lenzen et al., 2013; Wiedmann and Barrett, 2013), the World Input-Output Database—WIOD—(Timmer et al., 2015), and the Global Trade Analysis Project—GTAP—(Aguiar et al., 2019).

2.2.2. Ecosystem service valuation databases and ecosystem model parameter databases

A broad view of economic metrics linked to ES include economic welfare, national income, employment, factor productivity, competitiveness, poverty, resource dependence, income inequality, and others. The literature is dominated by efforts to estimate the monetary value of changes in ES, and to a lesser extent, their impacts on economies. Evidence on the links between ES and other economic metrics exists at the level of individual case studies for specific locations. We distinguish between ES valuation databases, which are collections of primary economic valuation studies, and ecosystem model databases, which are libraries of local datasets and parameters used to calibrate models to reflect specific country or area conditions.

In the first case, valuation studies provide an estimate of the monetary value of one ES or bundles of ES for a specific case study location (Raudsepp-Hearne et al., 2010). Typically, they apply a single valuation method such as stated or revealed preference, or cost-based methods (Banerjee and Bark, 2013). In some cases, two methods may be applied to value the same ES to cross-validate results. These studies are generally small-scale, limited to individual ecosystems, watersheds or protected areas, and are not necessarily generalizable. These studies tend to estimate values for marginal changes in ES provision or marginal changes in study site area or quality or for total ES provision over time. Values are typically estimated by beneficiary (e.g. USD/household/year), as the total value for the study site (e.g. USD/year) or as an average values per unit area of the study site (e.g. USD/hectare/year). These values can also be reported as a net present value calculated as the discounted stream of future values for a specific time period.

The Environmental Valuation Reference Inventory (EVRI) is a database of over 4,000 records with summaries of environmental and health valuation studies, and includes information on study locations, specific environmental assets being valued, methodological approaches, and estimated monetary values (Environment and Climate Change Canada, 2020). Values from the database are often used in benefits transfer, though two limitations are important to consider: (i) value estimates are not standardized to common units (e.g. USD/ha/year for a given price level) and so cannot be immediately compared or pooled without first undertaking standardization, and; (ii) some of the studies included in EVRI value environmental goods or bads other than ES, such as air pollution. The Ecosystem Service Valuation Database (ESVD) developed by the TEEB initiative provides a more readily usable dataset containing only valuation studies for ES and values have been standardized to common units; i.e. USD/ha/year at 2007 price level (de Groot et al., 2012; McVittie and Hussain, 2013).

The Mapping and Assessment of Ecosystems and their Services (MAES) initiative links socio-economic systems with natural capital through the flow of ES. MAES is in the process of mapping and assessing major ecosystems and their baseline ES; developing future scenarios depicting potential change; and valuing ES for scenario modeling. Efforts thus far have focused on the mapping and assessment of natural capital and ES (European Commission, 2015).

In the European context, there are various initiatives that support MAES including OpenNESS (Operationalization of Natural Capital and Ecosystem Services) which is developing operational decision-making frameworks that consider natural capital and ES; OPERAs (Operational Potential of Ecosystem Research Applications) to improve understanding of how ES contribute to well-being; VOLANTE (Visions of Land Use Transitions in Europe), which advances land system science to inform land use and natural resources related decision making; ESMERALDA (Enhancing ecoSysteM sERvices mApping for poLicy and Decision mAking), a flexible methodology to provide the building blocks for pan-European and regional mapping and assessment of ES, and; EU

Table 1
Selected ecosystem service parameters and sample global availability of data.

Dataset	Global default	References
Land Use Land Cover	Land Cover Maps - v2.0.7, ESA, CCI; 300 m ESA Climate Change Initiative dataset, annually for 1992–2015. http://maps.elie.ucl.ac.be/CCI/viewer/	ESA Climate Change Initiative - Land Cover led by UC Louvain (2017)
Digital Elevation Model; provides slope, elevation, aspect, and; basis for watershed delineation and other hydrological features.	Shuttle Radar Topography Mission (SRTM) 30-meter resolution. https://earthexplorer.usgs.gov/ https://dds.cr.usgs.gov/srtm/version2_1/SRTM30/	
Average annual precipitation	WordlClim, BIO12 of its bioclimatic variables. https://worldclim.org/data/bioclim.html	(Fick and Hijmans, 2017)
Root restricting layer depth	Absolute depth to bedrock (in cm) predicted using the global compilation of soil ground observations. Accuracy assessment of the maps is available in Hengl et at. (2017). https://data.isric.org/geonetwork/srv/eng/catalog.search#/metadata/f36117ea-9be5-4afd-bb7d-7a3e77bf392a	(Hengl et al., 2017)
Nitrogen loading by LULC (load_n); Phosphorous loading by LULC (load_p); Maximum retention efficiency by LULC for nitrogen and phosphorous (eff_n and eff_p). Critical distance over which each LULC retains nitrogen (crit_len_n) and phosphorous (crit_len_p).	Chaplin-Kramer et al. (2019) provides parameters for N. InVEST parameter database provides guidance on P. https://naturalcapitalproject.stanford.edu/software/invest N & P loading from agriculture is available from Lu et al. (2016). Maximum retention efficiency by LULC is the distance after which it is assumed that a patch of a particular LULC type retains nutrient at its maximum capacity. If nutrients travel a distance smaller than the retention length, the retention efficiency will be less than the maximum value eff_x, following an exponential decay (Sharp et al. 2018).	(Chaplin-Kramer et al., 2019) (Lu et al., 2016)
Average Annual Reference Evapotranspiration	Global Aridity Index and Potential Evapo-Transpiration (ET0) Climate Database v2, 1 km resolution. https://cgiarcsi.community/2019/01/24/global-aridity-index-and-potential-evapotranspiration-climate-database-v2/	(Hijmans et al., 2005)
Plant Available Water Content	Harmonized World Soil Database, Available water storage capacity in mm/m of the soil horizon; 1 degree spatial resolution: https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id = 1006	(FAO et al., 2009)
Rainfall erosivity index (R)	JRC dataset on Rainfall Erosivity in the World; 1 km resolution. Higher resolution data is available by contacting Panagos lead author. https://esdac.jrc.ec.europa.eu/content/global-rainfall-erosivity	(Panagos et al., 2017)
Soil erodibility (K)	See Global Soil Erosion Modeling Platform, GloSEM, for R, K, C, LS; 25 km resolution. https://esdac.jrc.ec.europa.eu/content/global-soil-erosion	(Borrelli et al., 2017)
Population density (beneficiary data)	WorldPop (100 m annual data for 2000–2020). https://www.worldpop.org/	
Revised Universal Soil Loss Equation (RUSLE) cover management (usle_c)	Cover management factor for the USLE. See cited papers and: https://naturalcapitalproject.stanford.edu/software/invest	(Borrelli et al., 2017; Yang et al., 2003)InVEST nutrient database.
RUSLE practice management factor (usle_p)	Practice management factor for the USLE. See cited papers and: https://naturalcapitalproject.stanford.edu/software/invest	IBID.

BON (Building the European Biodiversity Observation Network), which is generating a European Biodiversity Portal (European Union, 2013). Other databases with different degrees of coverage include the TEEB Ecosystem Services Project Database (van der Ploeg et al., 2010), ASEAN TEEB Valuation Database (Brander and Eppink, 2012), and Envalue from the National Ocean Economics Program (Colgan, 2007).

ES model databases are fundamental for underpinning ES modeling efforts since obtaining local data and parameters is usually the most time-consuming aspect of ES modeling, and without a repository for this data, this process is replicated time and time again for each new study.

Table 1 shows selected ES parameters that are needed in different modeling situations and sample global availability of data. Within the knowledge modeling environment (k.LAB) of ARIES (Villa et al., 2014), users can contribute annotated data that can be used by different models independently, thus providing a repository for ES model parameters and spatial and other data. The OPEN IEEM initiative led by the Inter-American Development Bank, in collaboration with ARIES, is developing a database with local ES data for the Latin American and Caribbean region (Banerjee et al., 2019a; Villa, 2019). The Natural Capital Project's InVEST initiative provides guidelines for the construction of ecosystem model parameter datasets and a database for some ES model parameters (Sharp et al., 2018).

2.2.3. Meta-analyses of ecosystem service economic values and global benefits transfer

Estimated values for ES vary across biomes, environmental conditions, socio-economic contexts, and valuation methods. Meta-analysis is a statistical method that combines estimates from multiple studies and systematically explores the variation in existing estimates and its determinants (Stanley, 2001). It also provides a means for estimating the value of ES and applying it to new study sites, which is referred to as value or benefits transfer (Desvousges et al., 1992; Johnston et al., 2017; Rolfe, 2006; Shrestha et al., 2007). Value transfer, and particularly meta-analytic value transfer, provides a viable means of estimating the value of ES at a global scale. The regression equation estimated through a meta-analysis can be interpreted as a value function, which is an equation that relates the value of an ES to the characteristics of the ecosystem and the beneficiaries. A meta-analytic value function can be used in conjunction with information on parameter values for the policy site where the value will be applied, to calculate the value of an ES that reflects the characteristics of that site. Many of the important determining characteristics of ES value vary spatially, and so the use of meta-analytic value functions for value transfer has proved useful in generating value maps as in Schägner et al. (2013).

Following the availability of underlying primary valuation estimates, there are many meta-analyses[2] examining values for wetlands (Brander

[2] The authors have compiled a list of over 50 meta analyses of ecosystem service values, organized according to author, year, ecosystems, ecosystem services, dependent variable, and explanatory variables, which is available in (Crossman et al. 2018)

et al., 2012; de Groot et al., 2012; Ghermandi and Nunes, 2013), forests and woodland (Barrio and Loureiro, 2010; Chiabai et al., 2011; Ojea et al., 2010), and fresh water (Johnston and Thomassin, 2016; Randall et al., 2008). There are relatively fewer meta-analyses that examine values for agricultural land (van Zanten et al., 2014), coastal ecosystems (Ghermandi and Nunes, 2013; Liu and Stern, 2008) and urban green space (Brander and Koetse, 2011).

A simpler approach is to use the primary ES valuation data in value transfer to estimate changes in ES values; this has been implemented at a global scale in numerous studies (Braat et al., 2008; Costanza et al., 2014, 1997; Ghermandi and Nunes, 2013). In general, this approach has been used in the analysis of differences in the total global value of ES over time or under alternative future scenarios. The analysis is static in that there are no dynamic feedbacks between the ecosystems supplying the ES and society and the economy.

As a limitation, transferred values may differ significantly from the actual values of the ES at the policy site (Rosenberger and Stanley, 2006). Brander (2013) notes that primary value estimates used in value transfer are themselves uncertain. Inaccuracies in primary valuation estimates may result from weak methodologies, unreliable data, analyst errors, and the whole range of biases and inaccuracies associated with improper application of non-market valuation methods. The number of reliable primary valuation results may be limited, particularly for certain ES and regions. Moreover, the process of transferring study site values to policy sites can also potentially result in inaccurate value estimates (Rosenberger and Phipps, 2007). So-called "generalization error" occurs when values for study sites are transferred to policy sites that are different without fully accounting for those differences. Such differences may be in terms of beneficiary characteristics including income, culture, demographics, education, or biophysical characteristics such as the quantity and/or quality of the ES and availability of substitutes.

Costanza et al. (2014) recognize that "basic value transfer is a crude first approximation at best", especially due to the limited number of valuation studies available and their highly variable quality. From their global approximation estimated about two decades earlier (Costanza et al., 1997) to the more recent one, the increase in valuation studies and the increased sophistication of methods alone had an important and positive impact on the unit value estimates (Costanza et al., 2014). The authors also recognize that while benefit transfer is a relatively simple approach, it glosses over details that would preferably (and even essentially) be addressed with "a more spatially explicit and dynamic approach" (Costanza et al., 2014, p. 154).

2.2.4. Towards an integrated approach: The system of Environmental-Economic accounting (SEEA)

The System of Environmental and Economic Accounts, the SEEA (European Commission et al., 2014), was developed to combine economic and environmental data in a common accounting framework that is consistent with the System of National Accounts (European Commission et al., 2009) given that they share accounting principles and concepts (Obst and Vardon, 2014). It is also compatible with the Balance of Payments and International Investment Position, the International Standard Industrial Classification of All Economic Activities (ISIC), the Central Product Classification, and the Framework for the Development of Environment Statistics. This unifying framework enables the measurement of the contribution of provisioning ES to the economy and the impact of economic activity on stocks of environmental resources and environmental quality in terms of emissions and waste.

Integrated economic-environmental frameworks have tended to focus on one provisioning ecosystem service of interest (e.g. water, timber or energy) at a time, and involving time consuming and costly data reconciliation and strong assumptions. With an integrated statistical data system like the SEEA Central Framework, the data reconciliation and assumptions required are minimized. As more countries construct their own SEEA accounts, this resource and time-intense process is averted and enables the more timely provision of evidence to support decision making at lower cost (Banerjee et al., 2016b).

The basic SEEA accounts cover forests and forest plantations, water, energy and greenhouse gas emissions, underground resources, fisheries, land, residuals, and environmental expenditures and transactions. With the measurement of stocks, the SEEA enables measurement of semi-inclusive wealth (Arrow et al., 2012; Stiglitz et al., 2010, 2009).

The SEEA overcomes two core limitations of the SNA with regards to natural capital and ES: (i) in the SNA, natural capital stock depletion is only accounted for as positive contribution to economic output; and (ii) the condition of natural capital is not accounted for thereby enabling ecosystem degradation to proceed undetected. Moreover, the development of SEEA and its compatibility with the SNA, the set of standards with which all countries measure economic performance, offers an unprecedented opportunity to advance the field of integrated economic-environmental modeling, while its international consistency will soon permit comparative analysis across-countries and time.

As an extension to the Central Framework of SEEA described above, the SEEA Experimental Ecosystem Accounting (SEEA EEA) framework moves beyond provisioning ES to consider non-material, regulating and cultural and aesthetic ES (UNEP et al., 2017; United Nations, 2014a, 2019). A key characteristic of SEEA EEA is that it is spatially explicit which is particularly relevant for the modeling of ES supply changes arising from policy and other shocks. The SEEA EEA integrates measures of ecosystem assets and flows with measures of economic activity and is consistent and complementary to the SEEA Central Framework and the SNA (Hein et al., 2020a).

As with the SEEA Central Framework, the EEA structure and basis of modeling is also compatible with the underlying data structure of CGE models. The SEEA EEA defines five main types of ecosystem accounts: the extent account (physical units), the condition account (physical units), the supply and use accounts (physical and monetary units) and the ecosystem monetary asset account (monetary units). SEEA EEA defines of the extent of an ecosystem asset and ecosystem type, which may be an aggregation of 15 classes of ecosystem assets, ranging from artificial/urban areas, tree-covered areas, to sea and marine areas (United Nations, 2014b).

As ecosystem accounting in the SEEA EEA framework is relatively new, there are an increasing number of examples, for 24 countries at last count (Hein et al., 2020a), at various scales and for different services, including the development of physical and monetary supply and use accounts for the Netherlands as a whole (CBS and WUR, 2015; Hein et al., 2020b) and ES supply and use accounts in Rwanda at the national and provincial level (Bagstad et al., 2020). Hein (2014) and Crossman et al. (2013) provide a useful overview of simple to complex biophysical modeling approaches for estimating ES supply in an ecosystem accounting context consistent with SEEA, which can be scaled up to the global level while maintaining consistency.

2.2.5. Models and databases integrating the macro-economy and ecosystems at the global and sub-global level

To capture the complex dynamics between economy, society and the environment, whole of economy, CGE models are powerful for multi-sectoral analysis and where policies are anticipated to have wide-ranging impacts (Arrow, 2005). Integrating a CGE approach with LULC change and spatially explicit ES modeling, it becomes possible to integrate feedbacks between economic, social and environmental systems.

At the national and subnational level, the IEEM Platform initiative integrates data organized under the SEEA in a dynamic CGE framework (Banerjee et al., 2019e, 2019b). One of the key advantages of IEEM is its integration of environmental data which is consistent with SNA through definitions, accounting principles and classifications. It is also customized with environmental modules that capture the particular dynamics of environmental resources and their use. For that reason, it also features, not only traditional economic performance measures, but also environmentally extended indicators, such as Genuine Savings (Banerjee, 2019; Banerjee et al., In preparation).

IEEM captures the dynamics of provisioning ecosystem services as inputs into economic processes and the returns to the environment in terms of emissions and waste. The IEEM Platform integrates non-material regulating and cultural and aesthetic ecosystem services by linking IEEM with spatial ES modeling (IEEM + ESM) (Bagstad et al., 2020; Banerjee et al., 2019b, 2019c). The linkage between the economic and spatial ES modeling components is made possible thorough LULC change modeling which is used to spatially allocate IEEM demand for land across a high-resolution spatial grid to produce LULC projections for a baseline and policy scenarios. These spatial datasets are used as the basis for ES model runs with ES modeling tools such as ARIES or InVEST.

The IEEM Platform has been used in various policy applications, including evaluating SDG strategies of the Guatemalan government (Banerjee et al., 2019a), impacts of strategies to reduced fuelwood consumption (Banerjee et al., 2019b) and various questions of tourism policy and investment (Banerjee et al., 2019d). Increasingly, IEEM is being applied by international and government institutions, including Central Banks, for the evaluation of public policy and investment (Quesada et al., 2019).

The linked IEEM + ESM framework has demonstrated the value-added of this approach, particularly with its ability to consider non-market regulating ecosystem services and its spatially explicit nature enabling spatial targeting of policy. Recent applications of IEEM + ESM have included evaluation of green growth strategies in Rwanda (Banerjee et al., 2020c), comprehensive analysis of an Amazon tipping point (Banerjee et al., 2020a), conservation strategies in Colombia (Banerjee et al., 2020a) and the decarbonization of agriculture, forestry and other land uses in Costa Rica (Banerjee et al., 2020b).

At the global level, the Global Trade Analysis Project (GTAP) database and a multi-regional CGE modeling approach is presented as the global analytical option. The GTAP 10 database provides a time series of snapshots of the global economy for each of four reference years: 2004, 2007, 2011, and 2014. It covers 121 countries and 20 aggregate regions (which include the remainder of countries of subcontinental areas for which no specific social accounting matrix exist, such as Rest of Central America, Rest of Caribbean, Rest of European FTA, etc.) of the world for each reference year, as well as 65 sectors, and describes global bilateral trade patterns, international transport margins, and protection matrices that link individual countries/regions. For each country/region, the database presents values of production, as well as intermediate and final consumption of commodities and services (Aguiar et al., 2019).

The GTAP project has developed models and tools for applications of the database, which includes the standard GTAP model and the Dynamic GTAP model. The standard GTAP model is a comparative static model that enables a one period simulation; the length of this period is determined by the model closure (short run versus long run). The dynamic version is temporally specific, and the model solves and generates results for each year of the simulation. This enables users to evaluate how changes in policy and exogenous shocks, technology, population and factor endowments affect economic trajectories of all countries/regions over a user-defined period.

As with IEEM, the GTAP database and model can be linked with spatially explicit ES modeling. This is facilitated by LULC data in the GTAP database, available for base years 2004, 2007, and 2011 (Baldos, 2017; Baldos and Hertel, 2012) and by GTAP-AEZ (Hertel et al., 2008) which modifies the standard GTAP model by spatially disaggregating LULC in agriculture, pasture and forestry by agro-ecological zone (AEZ) as defined by IIASA/FAO (Fischer et al., 2012). Another extension, GTAP-E, is used to evaluate impacts of greenhouse gases abatement policies, costs and spill-overs (Burniaux and Truong, 2002; McDougall and Golub, 2007).

Various initiatives have used GTAP's database and models, in combination with other sources of data to explore the policy implications for natural capital and ES. For example, Verburg et al. (2008) linked the GTAP model, the integrated assessment model IMAGE, and a LULC change model (CLUE-s) to explore climate change impacts on land use and species connectivity. Berrittella et al. (2007), Berrittella et al. (2006) have developed an extension to the GTAP model (GTAP-W) to evaluate groundwater scarcity in the context of international trade, positing that reductions in water supply would increase the relative price of water-intensive goods, thus shifting the competitiveness of some industries in global trade.

Steinbuks and Hertel (2012) have used the GTAP database to develop a global Forestry, Agriculture Biofuels Land use and Environment (FABLE) partial equilibrium model, for analyzing optimal global land use within a context of increasing demand for food, bioenergy, forest products and demand for non-provisioning ES and meeting greenhouse gas targets. Stevenson et al. (2013) applied GTAP-AEZ to estimate the land use impacts of germplasm improvements of staple crops. Results from their analysis showed that increases in cereal yields from Green Revolution technologies spared natural ecosystems from conversion to agriculture. The GTAP-AEZ framework has advantages over other global economic models of land use change such as IMPACT, the World Agricultural Trade Simulation Model (WATSIM), Agriculture and Land Use Model (AgLU), and the Forest and Agriculture Sector Optimization Model (FASOM). The reason for this is that a multi-regional CGE model underpinned by the GTAP-AEZ database considers general equilibrium impacts, in particular, land market effects, which were found to be relevant in the Stevenson et al. (2013) study. In a similar vein, the KLUM@GTAP framework links the Kleines Land Use Model (KLUM) with an extended version of GTAP to assess climate change impacts on cropland allocation (Ronneberger et al., 2009).

2.3. Scenario development

The integrated modeling approaches that we set forth in this paper require that any possible scenario under scrutiny be compared to a business-as-usual trajectory. These trajectories are constructed through a characterization of the economy at one particular point in time and how it is expected to evolve in the future based on the prior and expected actions of government, economic sectors and households. Proposed public policies and investments that are the subject of evaluation are then described as variations from that business-as-usual trajectory. This section on scenario development provides a common starting point for the integrated modeling approaches that we describe for application at the sub-global and global levels. There is a growing literature on development and implementation of scenarios to inform global and national-level policy discourse. Here we focus on those that are most relevant for exploring the linkages between the economy, society and environment at global and sub-global levels[3].

2.3.1. Sub-global scenario development

Sub-global scenarios are especially relevant for informing national level public policy and investment. While it is possible to explore trajectories of biodiversity loss and exogenous shocks, the real value-added of sub-global scenario modeling is in how it can help inform policy advice. Exploratory scenario construction begins with the preparation of qualitative narrative storylines that provide the descriptive framework from which quantitative scenarios can be formulated. Such qualitative scenarios are particularly valuable as the temporal scale under examination increases and there are greater chances that exogenous influences may introduce unforeseen systemic change, such as technological shifts (Rounsevell and Metzger, 2010).

[3] Notwithstanding, we encourage the practitioner to explore the scenario development literature in order to ensure applicability of modeling approaches to real problems(Dinerstein et al., 2017; Eitelberg et al., 2016; Fernandes et al., 2016; Montesino Pouzols et al., 2014; Newbold et al., 2016; Pereira et al., 2010; Rosa et al., 2017; Titeux et al., 2016; Veldman et al., 2015a, 2015b).

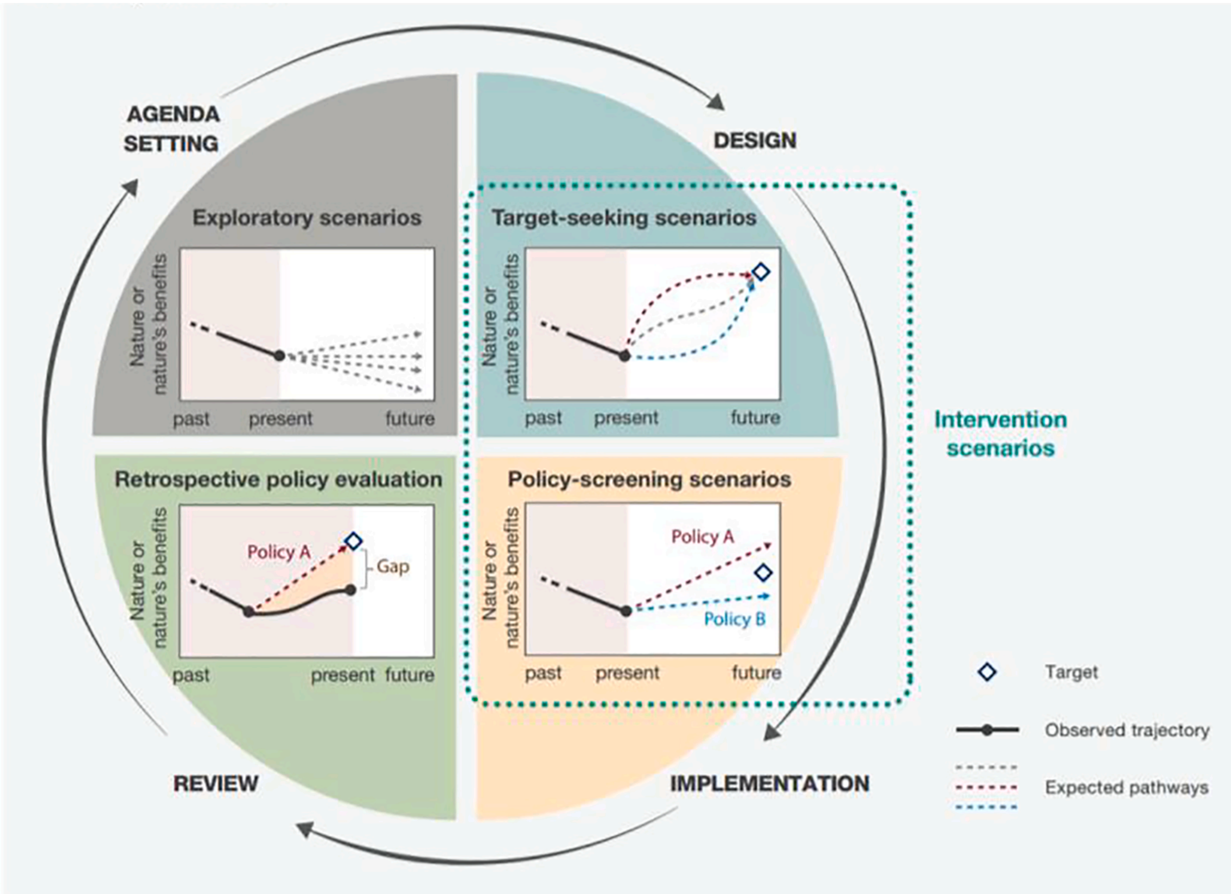

Fig. 1. Roles played by different types of scenarios corresponding to the major phases of the policy cycle. Source: (IPBES, 2016).

The choice of scenario and assessment type as well as the related methodological approach to scenario construction is highly contingent on where the practitioner finds themselves in the policy cycle. Fig. 1 shows that: (i) during agenda setting, exploratory scenarios could provide different outcomes for policy options open for discussion; (ii) during policy design, target seeking scenarios could show different ways of accomplishing a desired policy outcome, to meet SDG commitments, for example; (iii) during the implementation phase, policy-screening scenarios could help policymakers decide the best option to implement and understand the trade-offs, and; (iv) during the review phase of the cycle, scenarios could help determine, what would have happened had some other course of action been taken, as well as to evaluate the gap between current policy outcomes and hypothetical trajectories. While the SNA has provided an historically observed trajectory for key economic variables, the development of the SEEA now provides an historically observed trajectory for environmental variables which is critical for informing integrated economic-environmental futures scenario modeling.

2.3.2. Global scenario development

Scenario development at the global scale typically aims to capture broad possible trajectories, of changes in biodiversity for example. Fig. 2 shows that the starting point for scenarios is a narrative of socioeconomic development pathways, how they translate to direct drivers of ecosystem change including climate and land use change, and subsequent impacts on natural capital, biodiversity and ecosystem services.

A scenario framework was established by the research community to support integrated analysis of climate change and is organized around three key dimensions considered together in Integrated Assessment Models (IAMs): (i) the extent of climate change which is described by the Representative Concentration Pathways (RCPs). The RCPs are scenarios that quantify the range of potential future greenhouse gas emissions and concentration pathways; (ii) possible future socio-economic conditions, described as five Shared Socio-economic Pathways (SSPs), which depict different socio-economic projections and the challenges these pose to climate change mitigation and adaptation; and (iii) climate policy applications, described as Shared Climate Policy Assumptions which capture key climate policy attributes including targets, instruments and obstacles. Because GDP and other variables would be affected by the climate policies and climate change impacts under a particular Shared Climate Policy Assumption, modeling should be undertaken in a dynamic and endogenous way whereby a given policy affects future ecosystem service supply, which in turn has impacts on the economic system being modeled.

The SSPs were designed to represent different climate mitigation and adaptation challenges. The underpinning narratives and quantifications of each SSP also cover a wide range of economic, social, institutional, and organizational variables. However, using the SSP global pathways to project changes in natural capital and ES at a localized scale oversimplifies local social, economic and ecological feedbacks, as well as land-use dynamics. Acknowledging this limitation, IPBES (2016) calls for new scenario development approaches that couple bottom-up, diverse, multi-scale scenarios within a consistent global scenario context (Kok et al., 2017; Rosa et al., 2017). A bottom-up-top-down approach would build on many local scenarios, stakeholder networks and local research capacities, and place these in a global context that focuses on the interactions among local

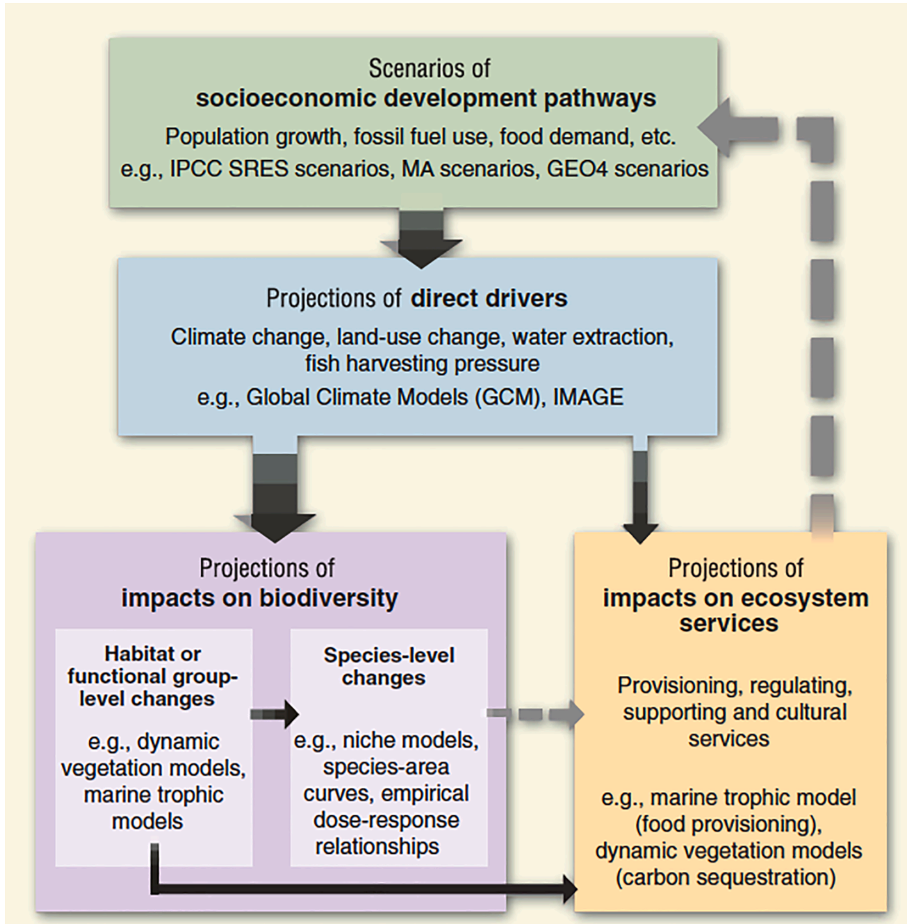

Fig. 2. Overview of methods and models commonly used for constructing biodiversity scenarios. Dashed grey arrows indicate linkages that are frequently absent in current biodiversity scenarios. Source: (Pereira et al., 2010).

trajectories and global dynamics.

3. Global and sub-global methodological approaches

The previous sections assessed modeling approaches for estimating impacts of changes in biodiversity, natural capital and ES and found that although they provide a good understanding of biological processes, they generally consider socioeconomic factors as drivers of degradation and do not acknowledge that they are part of the same complex system. ES valuation databases provide elements to value ES, though their robustness is highly variable due to methodological and data issues. ES model parameter databases allow linkages to be made between natural phenomena and economic variables and reduce barriers to entry for ES modeling substantively. Integrated data frameworks such as the SEEA combine natural capital and socioeconomic information.

A key challenge for integrated modeling to provide strong evidence to inform the post-2020 agenda is to capture feedbacks between ecological and economic systems. These systems do not operate in isolation and changes in one affect the other in important ways. In what follows, we present a detailed view of how this complex systems approach may be operationalized both at the sub-global and global levels. Our recently developed IEEM + ESM approach is one such approach which we present in the next section. The IEEM + ESM approach enables integration of economic and ecological systems and feedbacks between the two. We have implemented various studies with this approach, at the sub-global level (Amazon biome), national level (Rwanda, Costa Rica, Colombia and others) and at the subnational or local level (Colombia, Rwanda and others). At the global level, the basic IEEM + ESM workflow presents a blueprint for how such an integrated approach could be developed at the global level, based on global data organized by the GTAP project (Aguiar et al., 2019) and increasingly available global ecosystem service modeling tools and parameter databases (Chaplin-Kramer et al., 2019).

3.1. *A sub-global integrated modeling approach*

An integrated socioeconomic and environmental approach that uses consistent definitions, classifications and indicators to describe each system is at the core of a modeling approach that describes economy, society and environment as a complex system. The IEEM Platform linked with ES modeling- IEEM + ESM- is one such complex systems approach that leverages the benefits of the consistency between SEEA and SNA to generate spatially explicit estimates of key indicators of sustainable economic development, including wealth and natural capital metrics. The OPEN IEEM initiative adopts a paradigm of open sharing of data and models and FAIR data principles which will contribute to shifting efforts toward methodological innovation and stronger analysis and away from replicating efforts of previous work (Bagstad et al., 2020; Banerjee et al., 2019a).

The motivation behind the development of the IEEM Platform was the integration of ES in an economy-wide CGE framework to account for the environmental impacts of public policy and investment. In the past, this integration has occurred considering one natural capital asset at a time (e.g. forests), while data was often obtained from various sources requiring significant data reconciliation efforts (Banerjee et al., 2016a). The IEEM Platform advances standard CGE models in four important

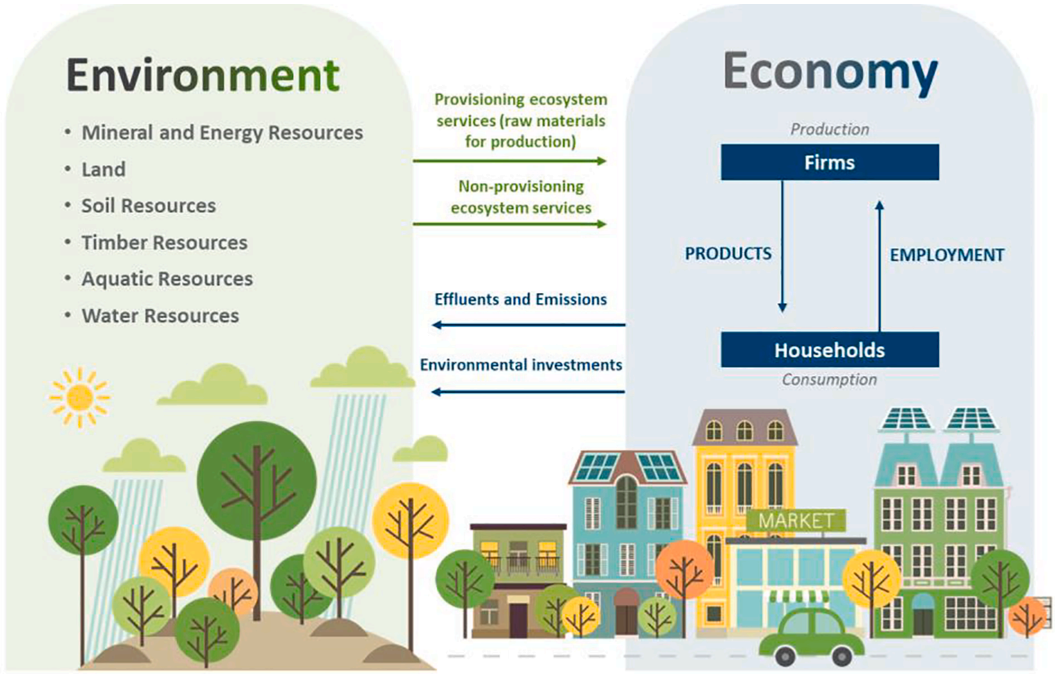

Fig. 3. Economy-environment interactions captured in IEEM.

ways. First, it integrates rich environmental data organized under the SEEA, which is consistent and compatible with the SNA- the basic building block of any CGE model. The integration of the SEEA in IEEM obviates the need for resource-intensive data reconciliation which can require strong assumptions, while reducing the time and resources required to deliver timely advice to policy makers. Second, the indicators IEEM generates speak to Ministers of Finance responsible for national budgets, with metrics such as GDP, employment, income and government revenue. IEEM delivers additional metrics including genuine savings that address the critiques of GDP and speak to the sustainability of public policy and investment.

Third, IEEM contains specific natural capital modeling modules to capture their specific dynamics (Fig. 3), as well as additional features to track return flows from the economy to the environment as well as environmental investments. Natural capital-based economic sectors have different dynamics when compared to conventional economic activities, for example: forests grow, they can be managed and enhanced, they can be harvested, deforested and degraded. In addition to these modules, environment-economy interactions are further captured through the explicit consideration of return flows of waste and residuals that are generated through economic processes and returned to the environment. Investments in mitigating environmental damages and environmental conservation and preservation are also accounted for.

Fourth, with the integration of SEEA LULC data in IEEM, our IEEM + ESM approach enables estimation of policy impacts on non-market and non-material ES, such as regulating and cultural ES. In a recent application to Green Growth Strategies in Rwanda, we demonstrated the additional insights of the IEEM + ESM approach in shedding light on economic and ES impacts of policy, including impacts on carbon capture, water yield and nutrient and soil retention (Banerjee et al., 2020c).

The IEEM Platform is publicly available[4] and IEEM's mathematical structure is documented in Banerjee & Cicowiez (2020). The database for IEEM is an environmentally extended Social Accounting Matrix (SAM) and its construction is described in Banerjee et al. (2019b). A user guide for a generic version of IEEM, applicable to any country with the corresponding database, is available in Banerjee & Cicowiez (2020). IEEM has been applied to hundreds of questions of public policy and investment and has demonstrated its robustness in a range of applications[5].

The workflow for implementing IEEM + ESM is presented in Fig. 4; we contextualize it with an example applying the approach to two of the Guatemalan Government's strategies to make progress toward SDG 2 of Zero Hunger through the expansion of irrigated agriculture and SDG 15, Life on Land, through increasing forest plantation cover. Fig. 5 presents the main elements of scenario design. Using a multi-regional version of IEEM, the first step is to generate a baseline projection, which is the reference scenario to which all subsequent scenarios are compared. The full period of analysis is from the year 2020 to the year 2035, however, in order to incorporate erosion mitigation services in the baseline, we run the IEEM baseline and scenario projections in 5-year periods[6].

Run for the first 5-year period, 2020 to 2025, IEEM produces baseline results for economic and natural capital indicators and demand for land. The projected estimates of demand for land are allocated spatially with the LULC change model. An overview of the LULC modeling approach is provided in Fig. 6. The LULC change model is comprised of three submodeling routines, namely: (i) a suitability model calibrated with local data to estimate the probability that one LULC class will transition to another class; (ii) transition rules to reflect the social, economic and environmental context of the region (e.g. proximity to population centers, proximity to roads, maximum slope constraints, etc.); and, (iii) demand for land by subnational unit which is estimated with IEEM. The outputs of this step are one LULC map for 2020 and one map for 2025.

These base maps are then used as inputs into the ES modeling to estimate ES supply for 2020 and 2025. Carbon storage, sediment

[4] All IEEM models, databases and documentation will be available here: https://www.iadb.org/en/topics/environment/biodiversity-platform/the-idbs-biodiversity-platform%2C6825.html

[5] For a sample, see: https://publications.iadb.org/en/publications?keys=IEEM

[6] Note that the baseline projection implemented with IEEM here is described in 5-year time steps. This enables us to include the economic impacts of changes in ES supply, erosion in this case, in the baseline. This approach enables us to directly estimate the scenario impacts on ES supply.

Fig. 4. IEEM + ESM workflow.

retention, nutrient retention, water yield, pollination, flood regulation and biodiversity (proxied by mean species abundance) are common ES that can be modeled with various ES modeling tools. Given the agricultural focus of the policies under consideration, we focus on erosion mitigation services in this example. The LULC map is the main variable of change through time in this ES modeling experiment. Though not considered here, because it is not directly related to the scenario, climate change could also be considered in the parameterization of some ES models as we have implemented in more recent work (Banerjee et al., 2020c). ES supply results are generated at the national level and at the level of each of Guatemala's 22 Departments for 2020 and 2025.

The next step is to implement the policy scenarios in IEEM for the period 2020 to 2025, which in this case are the interventions to expand irrigated agriculture and forest plantations. We implement the shock in IEEM for the first time period of 2020 to 2025 and generate estimates of impacts on the economy, natural capital and demand for land. The demand for land for each scenario is spatially allocated with the LULC change model to generate a new LULC map for each scenario for the year 2025. The ES model is run with these new maps for 2025 and ES supply is estimated for each scenario for that same year. Based on results from the baseline projection in 2025 and scenario results from 2025, the difference in the indicator of interest, tons per hectare per year of soil erosion in this case, is calculated for each scenario. The result of this calculation is the change in ES supply attributable to the scenarios.

Changes in ES supply affect the economy through various mechanisms. Increased soil erosion for example reduces agricultural productivity (Borrelli et al., 2017; Panagos et al., 2018, 2017, 2015; Pimentel, 2006; Pimentel et al., 1995). Increased soil erosion and nutrient run-off affect water quality which can have implications for water treatment costs, human health and tourism values (Chaplin-Kramer et al., 2016; Cicowiez et al., 2019; Keeler et al., 2012; Meals et al., 2010). In this case study, we focus on how changes in erosion mitigation ES affect agricultural productivity and in turn, the economy. To estimate the erosion impact on agricultural productivity, using the erosion map generated through the ES modeling exercise, we identify all those pixels in the base and scenarios that exhibit severe erosion (Fig. 7) which is defined as areas exhibiting erosion greater than 11 tons/ha/yr (Panagos et al., 2018). By Guatemalan Department, we then sum the total areas in the base and scenarios exhibiting severe erosion and take the difference. A positive result indicates erosion has increased while a negative result indicates erosion has decreased.

Based on the area of increased or decreased erosion, we estimate an agricultural productivity shock for each Department. The magnitude of the shock is based on the literature on field trials assessing erosion impacts on agricultural productivity summarized by Panagos et al. (2018); based on this, we use an agricultural productivity shock of 8%. This agricultural productivity shock is applied to the increased/decreased area exhibiting severe erosion and is implemented in IEEM in the year 2026. New results are generated for the period 2026 to 2030 for economic and natural capital impact indicators and demand for land. The LULC change model and ES model are run for the 2026 to 2030 period, and changes in ES supply and how they translate into changes in agricultural productivity are estimated as described above. This iterative process continues until the end of the analytical period.

The outcome of the iteration between models described above is the scenario impacts on the economy considering changes in both natural capital stocks and ES service supply. This information is also valuable when implementing a cost-benefit analysis and enables the full economic and environmental impact of a policy to be considered in a robust and transparent way. Fig. 8 shows the economic impact of erosion through the time period for each scenario. In the case of the SDG 2 strategy, there is a reduction in erosion mitigation services and the economic loss is valued at US$129,704 by 2035. The expansion of

Fig. 5. Implementing SDG scenarios in IEEM.

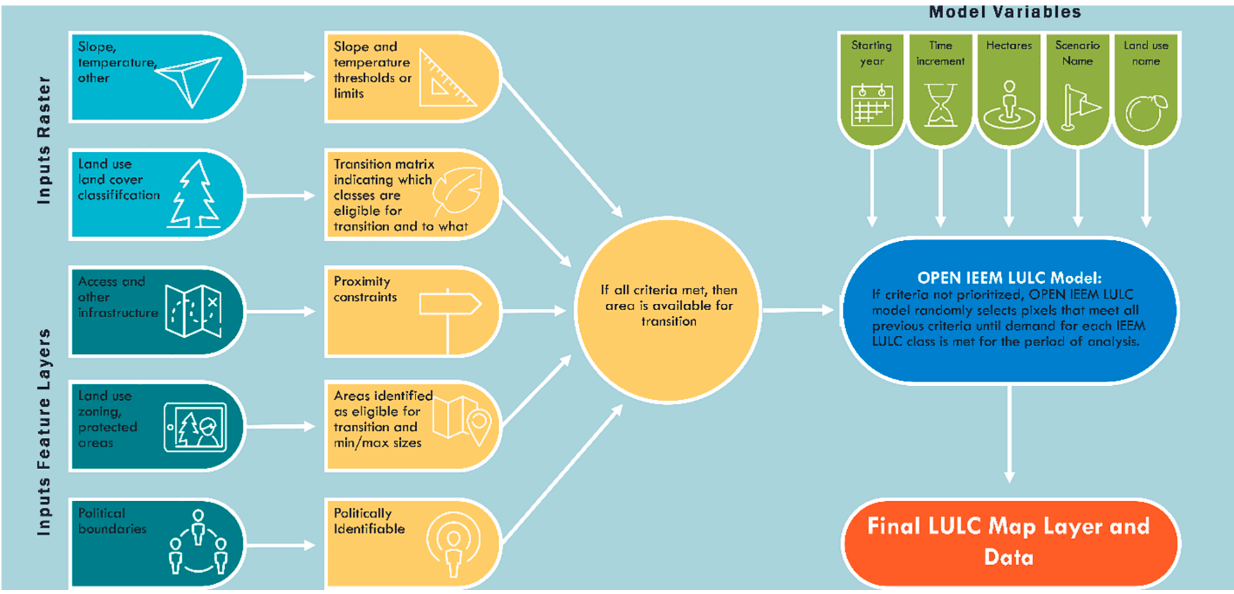

Fig. 6. OPEN IEEM Land Use Land Cover Change Model.

forests in progressing toward SDG 15 on the other hand generates additional erosion mitigation services valued at US$312,027. This result is evidence of the additional non-market values standing forests generate; recognizing the monetary value of standing forests, beyond timber, has long been a critical issue in generating economic arguments of forest conservation and sustainable management.

3.2. A global integrated modeling approach

The global integrated economic-environmental modeling approach we present here follows the IEEM + ESM workflow closely. For the proposed global approach, the GTAP database is the natural starting point, which may be used with the dynamic GTAP model or a similar dynamic multi-regional CGE model. The approach proposed here would link the GTAP database and model with LULC change and ES modeling. As with the IEEM + ESM approach, the workflow would begin with scenario design and implementation in the CGE model.

We present the global integrated approach through a hypothetical

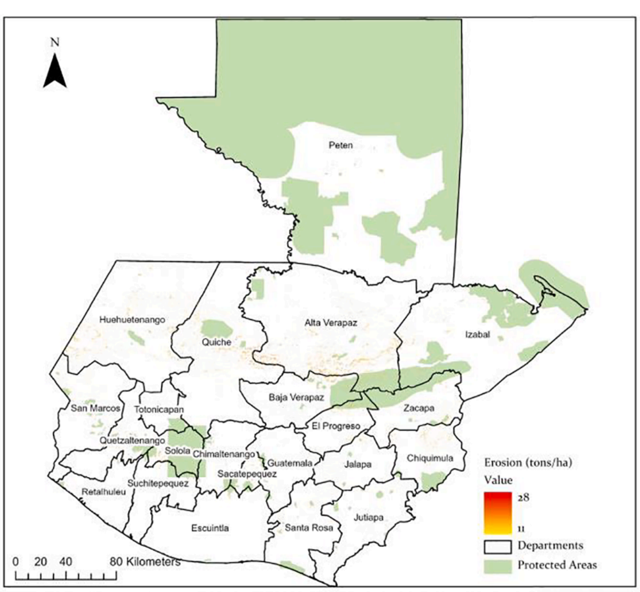

Fig. 7. Severe erosion greater than 11 tons per hectare in baseline in 2025.

narrative. We assume a business as usual scenario where past trends of economic and population growth continue; biodiversity continues to decline at rates observed in recent history with implications for economic development. There would be many mechanisms or transmission pathways by which biodiversity decline could affect economic prosperity. For example, reduced genetic diversity of agricultural crops and gene banks could have implications for the frequency and extent of crop/agricultural losses due to pest/disease outbreak. Lower genetic diversity could result in a slower rate at which more productive and resilient crops are developed, thereby slowing growth in agricultural productivity and the pace at which food security is achieved. Reduced pollinator diversity could have implications for future agricultural yields.

Fig. 9 describes how reduced biodiversity and in this example, pollinator abundance, would be implemented in the dynamic GTAP-based modeling framework while endogenizing its impact on the global economy. The first step in the workflow would be to generate the baseline forecast informed by expectations of GDP, population and labor force growth, and other socioeconomic projections considered relevant to the experiment, for example, rates of deforestation. As with the IEEM + ESM approach, models would be run on a periodic (5-year time steps, for example) basis and a first model run would provide estimates of all standard economic indicators including GDP, employment and income for each country. With GTAP-AEZ (described in Section 2.2.5), projections of demand for land would be generated. These changes in LULC would be spatially allocated across the globe to generate LULC maps.

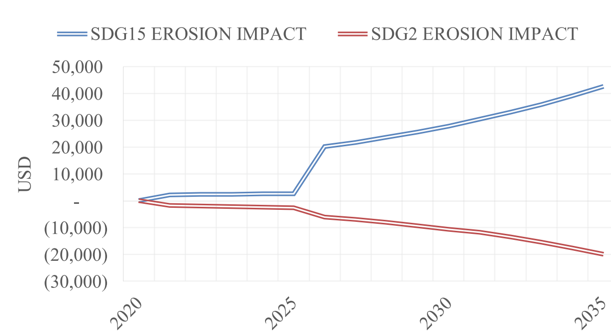

Fig. 8. Value of Erosion Mitigation Services.

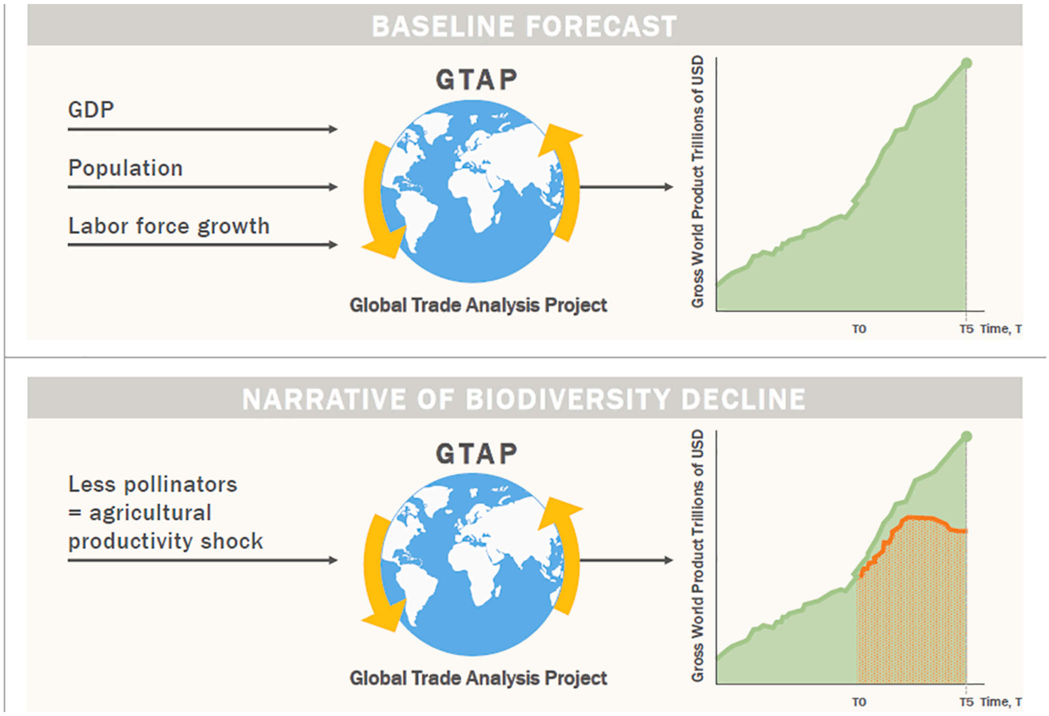

Fig. 9. Implementation of narrative of pollinator abundance in GTAP as exogenous shock.

There are various tools that could be used for this spatial allocation as described in this paper, including the CLUMondo model presented in Section 2.2.1.

The next step would be to develop scenarios, where in this case, we would be concerned with understanding the economic impact of reduced biodiversity, specifically related to pollinator abundance. One potential scenario could examine a future state where deforestation were to occur at a faster rate than that projected in the baseline. This would reduce species habitat, species biodiversity and pollinator species abundance and richness globally. To operationalize this scenario, we would implement GTAP and GTAP-AEZ with the scenario-based estimates of deforestation to generate new projections of LULC change for the first period. Thus, for the first time period, we would have one LULC map for the baseline in the year 2025 and one for the deforestation scenario in 2025. In addition, GTAP would generate all standard economic indicators for the baseline and the deforestation scenario.

The next step in the workflow would be to implement the ES model for crop pollinators. In implementing the pollinator ES model, the LULC map would the main variable of change through time. Climate change could also be considered, however in the case of the pollinator ES model, climate change would be manifested through changes in LULC. The pollinator model would be run for the baseline and for the deforestation scenario for the first period, and the difference between the two model runs would yield the estimated change in ES due to accelerated deforestation. In this case, this difference would be expresses as the difference in pollinator abundance and the pollinator yield index (Sharp et al., 2018). Next, to dynamically endogenize feedbacks between changes in ES and the economy, we would consider how changes in pollinator abundance affected agricultural productivity for pollinator-dependent crops.

We would consult the relevant literature to relate a change in pollinator abundance with a corresponding impact on agricultural productivity and develop a agricultural productivity shock on the basis of this relationship (e.g. Kennedy et al., 2013; Klein et al., 2007; Kremen, 2005). Based on the average reduction in pollinator abundance over the 5-year period, the agricultural productivity shock for each pollinator-dependent crop would be estimated. The pollinator yield index would be used to determine how the productivity shock would have to be applied across a given LULC class. This productivity shock would then be implemented in GTAP in years 6 through 10 and results would be generated for this second period in terms of economic indicators as well as demand for land. Demand for land would be allocated using the LULC change model. The pollinator ES model would be run once again to generate new estimates of pollinator abundance for the years 6 through 10. Based on new estimates of pollinator abundance, the agricultural productivity shock would once again be estimated and implemented in GTAP beginning in year 11 through to year 15. This iteration would continue until the end of the analytical period of the experiment. By endogenizing feedbacks in this way, we would fully capture how the socioeconomic system interacted with the ecological system in a dynamic and meaningful way[7].

4. Discussion and conclusions

The year 2020 is a critical year with the review and renewal of various international commitments including the SDGs, the CBD and the Paris Agreement. The post-2020 agenda has the potential to be informed by more robust analytical approaches that capture the interactions between the economy, society and the environment. In this paper, we have outlined the state of the art in available models and datasets that lay the

[7] A variation of this approach has been implemented by Johnson et al. (2020) using the GTAP database and the static GTAP model. Their approach differs from that just described, however, in that it takes LULC and ES change as the starting point and implements ES shocks in the static GTAP model. This contrasts with our approach which begins with the CGE model with the workflow driven by the implementation of policy shocks in the dynamic CGE model. Furthermore, Johnson et al. (2020) draw LULC change projections from previous work undertaken through the World Climate Research Program's Coupled Model Intercomparison Project (Eyring et al., 2015), which creates some inconsistencies between the characterization of the economy through the CGE model and demand for land characterized by the LULC data. As a result of this and the use of a static CGE framework, this approach does not enable the integration of feedbacks between the economy and changes in ES supply.

groundwork for future applied analytical work. With a complex systems perspective, we find that we can represent system component interactions by integrating whole of economy CGE models with spatial LULC and ES modeling. Both national and global scale analysis have a role to play in informing policy discourse and advocacy at the global level and specific public policy and investment strategies at the national and subnational levels.

With the increasing application of the SEEA in countries world-wide, there is growing opportunity to systematically capture the relationship between economies and the natural capital base upon which they depend. As SEEA implementation experience is gained, the possibility of temporal and cross-country analysis becomes a possibility. As a database, the SEEA poses significant advantages for economy-wide modeling approaches given its consistency with the SNA, and its widespread usage. The development of an international ES Accounting standard currently underway, also consistent and compatible with the SEEA and SNA, make reporting progress on economic, social and environmental goals within a consistent framework with shared concepts and principles a distinct possibility in the short term.

To underpin the proposed integrated economy-wide and spatial ES approach, further development of ES parameter databases is important. While global databases do provide all parameters required to run most basic ES models, the availability of local parameters in some cases can improve the robustness of the results and their local acceptance. Local time series data for environmental variables is critical for ES model validation. Continued development of valuation databases and improvements in the primary valuation studies that they are drawn from is of great use, particularly to inform the cost benefit analysis that most governments implement. The availability of natural capital and ES valuation data is an important surrogate when new modeling or primary studies are not possible under tight timelines that policy and decision-makers usually face.

Both the national and global scale approaches proposed here can provide critical insights to inform policy discourse. Currently, significant expertise across scientific disciplines is required to implement these analytical approaches. Efforts are underway, however, to simplify tools and their application, for example with the OPEN IEEM initiative and its integration of LULC and ES modeling, the number of data hand-offs required is reduced. Through OPEN IEEM, IEEM and ES models for over 20 Latin American and Caribbean countries will be made open access which will greatly reduce the time and cost typically required to generate economy-wide and ecosystem services assessments. Both these advances will greatly increase the timeliness of policy advice and reduce the costs and barriers to using these tools to inform policy. Furthermore, and fundamental to the OPEN IEEM strategy, building capacity within developing countries is a key to enable countries to generate their own analysis with their own expectations, assumptions and aspirations for the future. This diversity of perspective is important for countries to take ownership of the analytical processes and results and avoid the emergence of any one particular uncontested world view.

Endogenizing feedbacks between the economic system and changes in natural capital stocks, the condition of natural capital stocks and the ES they provide is a critical area for further research. Two lines of work are important, the first involves outlining the mechanisms by which changes in ES supply affect the economy. Some basic mechanisms such as the erosion and pollinator abundance impacts on agricultural productivity were considered here, though there are many other mechanisms possible such as flood risk impacts on infrastructure investments and avoided damage costs, interactions between fertilizer application in agricultural fields and water quality and the eutrophication of water bodies, and air quality and other environmental quality elements and their impacts on tourism demand to name a few. The mechanics of these interactions need to be formalized quantitatively. Once more experience is gained in this area, these interactions and related costs and benefits can be more readily incorporated in policy and decision making, which often happens at a pace much quicker than complex modeling may be readily undertaken.

Sensitivity analysis is another important avenue of work, since the battery of tests that are common in econometric analyses has limited application in system-wide modelling. It is important to test how the combination between economic-environmental modelling, Lan Use Land Change modelling and Ecosystem Service Modelling is affected by changes to their parameters in systematic ways, while at the same time analyzing how they fare against the results provided by other types of models such as the ones described in the second section of this paper.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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